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DETERMINATION OF DEFECTS IN SILICON *p-i-n* DETECTORS OF NUCLEAR RADIATION

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ABSTRACT

Defects in *p-n* junction of silicon *p-i-n* detectors are investigated by means of electrophotography and electrochemical depositing of copper. The study of the defects is associated with electric characteristics of detectors.

Introduction

Silicon *p-i-n* detectors of nuclear radiation, *p-n* junctions obtained /3* by drifting lithium ions in an electric field (Ref. 1), have lately been applied a great deal in nuclear spectroscopy (Ref. 2).

In the process of investigating the formation mechanism for a region sensitive to radiation, we have discovered some structural defects of the *p-n* junction in silicon *p-i-n* detectors. In the present article we present the results derived from determining the defects, arising during the drift of lithium ions in a *p*-type silicon single crystal, and the dependence and connection of these defects with some electric characteristics of the *p-n* junction in silicon *p-i-n* detectors.

Determination of the *p-n* Junction Defects in Silicon *p-i-n* Detectors, and Experimental Results

The defects of the *p-n* junction in silicon *p-i-n* detectors were discovered during the drift of lithium ions when the boundary of the *p-n* junction was developed by three methods simultaneously:

(1) Development with dry negative and positive electrophotographic developers (Ref. 3);

(2) Development with a liquid electrophotographic developer (Ref. 4);

(3) Development using the method of electrochemical copper deposition (Ref. 5).

In Figure 1 we show a microphotograph of the boundary of the *p-n* junction in specimen No. 9, where a defect was discovered after drifting lithium ions for 29 hours. Because of the presence of inhomogeneities in the silicon single crystal, the boundary of the *p-n* junction fluctuated. The development of the *p-n* junction was effected with the aid of a dry positive electrophotographic developer PS-1. Specimen No. 9 was cut perpendicularly to direction

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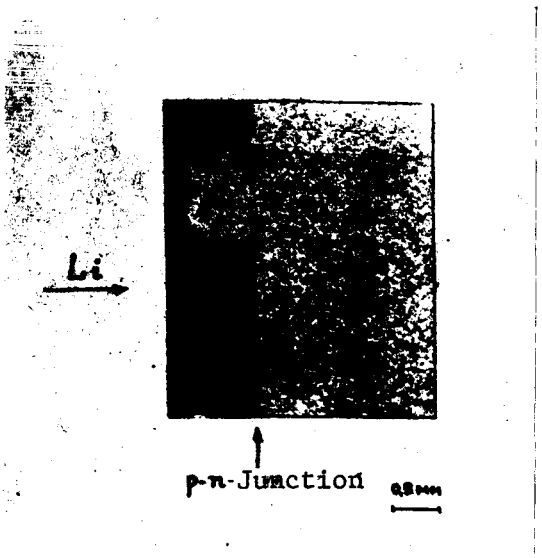

Figure 1

Defect of the p-n Junction in the Silicon p-i-n Detector (Specimen 9) Developed With a Dry Positive Electrophotographic Developer. The arrow shows the direction of the diffusion and drift of lithium ions. Duration of the drift -- 38 hours.

(III) out of a bar of p-type silicon, which was developed by the method of /4 Chokhral'skiy, and was located at a distance of 7 cm from the beginning of the bar. The specimen was in the form of a plate 5.8 mm in thickness and 1.80 cm in diameter with a specific resistance of ρ = 259 cm. The lifetime of the principal carriers τ = 150 microsec.

The diffusion of lithium was conducted in an atmosphere of argon at a temperature of T = 363°C for 30 minutes. The conditions of the lithium ion drift for this specimen were as follows: temperature, T = 130°C; voltage of the reverse bias, U = 100 V; time, t = 36 hours. The resulting thicknesses of the separate layers of the detector had the following values (irrespective of the defect): thickness of the compensated region w_i = 1.104 mm; thickness of the n-region w_n = 124 micrometers.

A defect of the p-n junction, discovered in specimen 9 after 29 hours of drift, increased after 36 hours of drift.

The appearance of the p-n junction in a second detector (specimen 5) was also rather strange. A defect was discovered after 50 hours of lithium ion drift. The boundary of the p-n junction was developed successively with a liquid electrophotographic developer (Figure 2a) with a voltage of the reverse bias of U = 100 V, and with the aid of the electrochemical deposition of copper, without any voltage being applied (Figure 2b).

Specimen 5 was also cut perpendicularly to direction (III) from another bar, and was located at a distance of 3 cm from the beginning of the bar. The specific resistance of the sample was ρ = 422 ohm cm; the lifetime of the

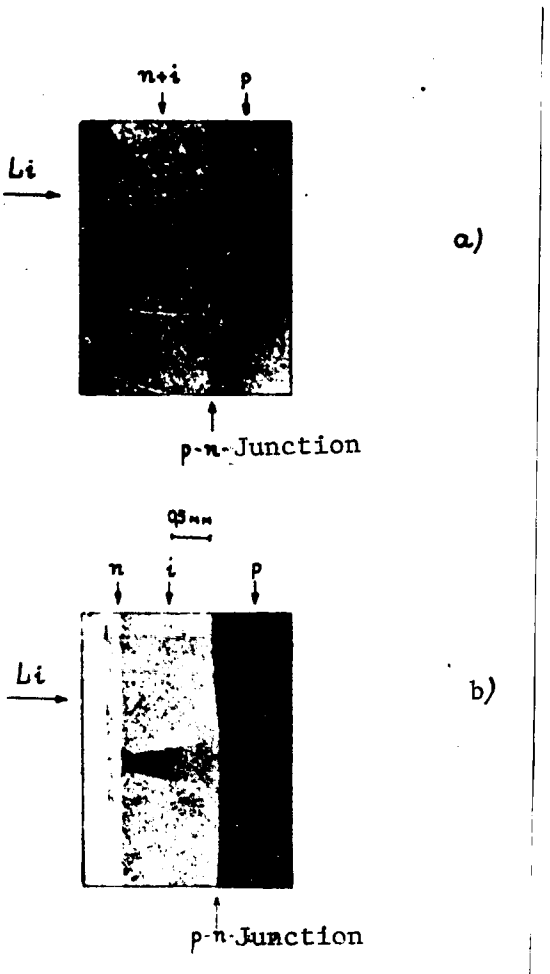

Figure 2

Defect of the p-n Junction in the Silicate p-i-n Detector (Specimen 5) Developed With a Liquid Electrophotographic Developer (a) and Electrochemical Deposition of Copper (b). Duration of the drift -- 50 hours.

principal carriers was τ = 470 microsecs. The diffusion and drift of the lithium ions was conducted under the following conditions: diffusion temperature T = 300°C; duration of diffusion annealing t = 30 minutes; drift temperature, T = 138°C; voltage of reverse bias, U = 97 V; duration of drift, t = 50 hours. The mean thicknesses of the separate layers (irrespective of the defects) have the following values:

$$w_n = 197 \text{ micrometers}; \quad w_i = 1.316 \text{ mm}.$$

The discovered defects of the p-n junction in a single silicon crystal of p-type were propagated in the direction opposite to that of the drift of lithium ions, and reached only the n-region. This is well illustrated in

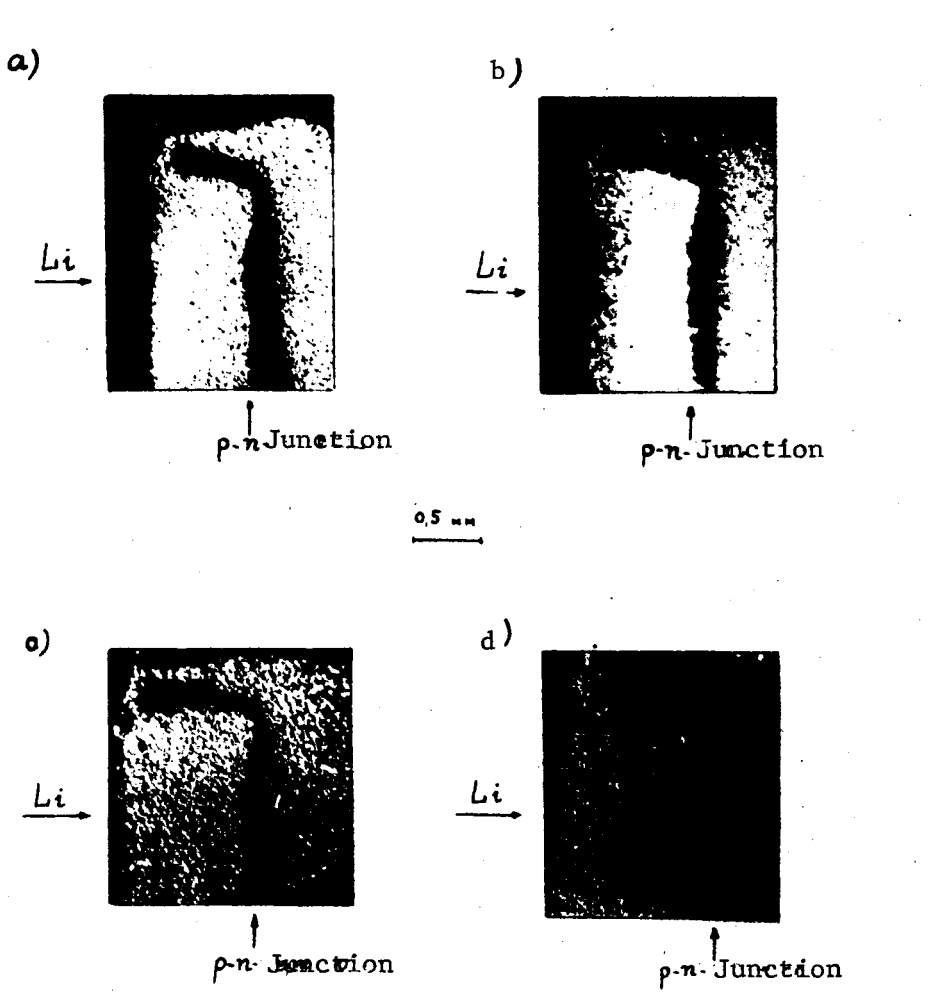

Figure 3

Change in the Defect of the p-n Junction in the Silicate p-i-n Detector (Specimen 14) During the Drift of Lithium Ions. (a) After 14 hours of drift; (b) After 24 hours of drift; (c) After 34 hours of drift; (d) After 44 hours of drift. The p-n junction was developed with a liquid electrophotographic developer. The arrow on the left shows the direction of the diffusion and drift of lithium ions.

Figure 2b.

In specimen 14, a defect near the end of the specimen was discovered during the drift of lithium ions. Figure 3 shows a microphotograph of the boundary of the p-n junction for this specimen. The form of the defect was clearly retained from 14 hours to 44 hours of the drift of lithium ions; only

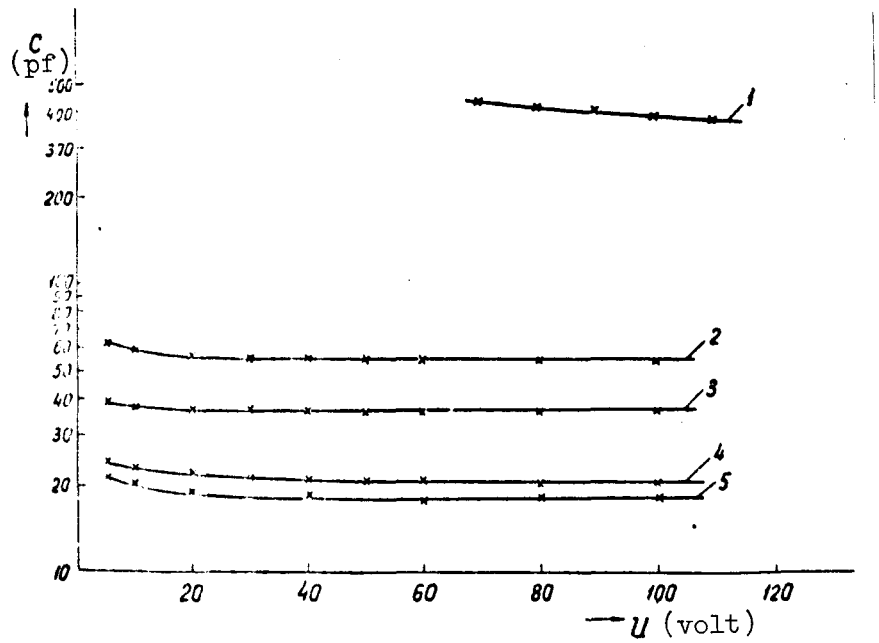

Figure 4

Capacitance Characteristics of the Silicate p-i-n Detector (Specimen 5) During the Drift of Lithium Ions. 1 -- After diffusion; 2 -- After 4 hours of drift; 3 -- After 10 hours of drift; 4 -- After 30 hours of drift; 5 -- After 50 hours of drift (defect discovered).

the depth of the p-n junction deposit increased. The conditions of diffusion and drift of lithium ions for specimen 14 were the same as those for the specimens in which no defects of the p-n junction were discovered.

Discussion of the Results

It is usually assumed that any defect of the p-n junction of a detector should introduce a change in its electric characteristics. This has not been observed by the author. Figure 4 gives the capacitance characteristics of /5 specimen 5. It may be seen that no change in the appearance of the curve took place during the drift, regardless of the presence of a defect in the p-n junction of the detector (see Figure 2). The appearance of the current-voltage characteristics of detectors with defects of the p-n junction did not change either. In some silicon p-i-n detectors, however, during the drift of lithium ions, defects were observed in the form of a crack. In this case, the current through the specimen increased immediately and a breakdown took place.

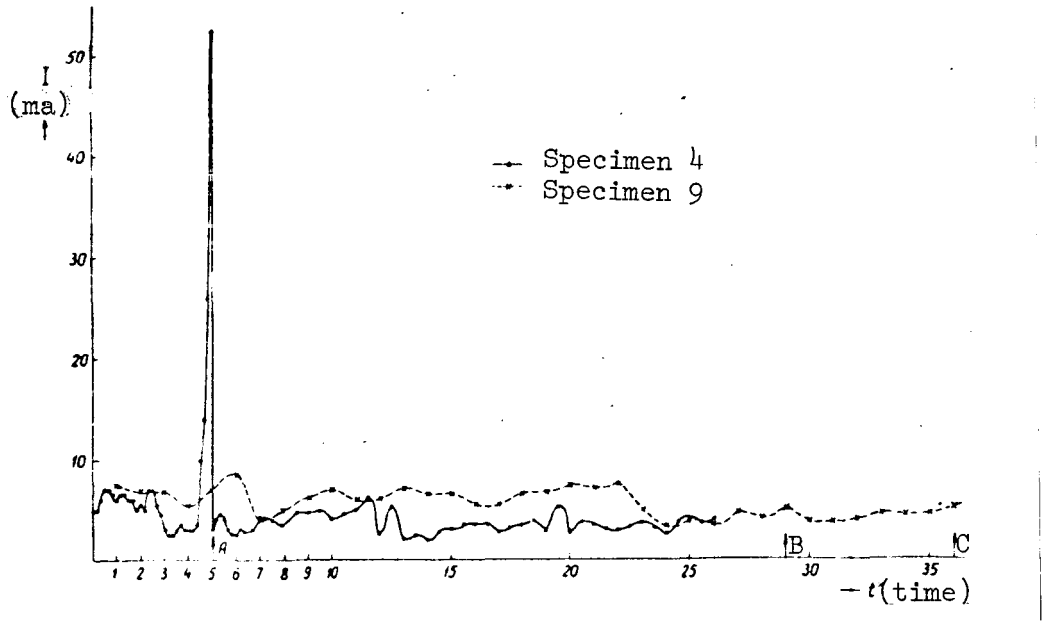

Figure 5

Current of Reverse Bias Through Specimens 4 and 9 During the Drift of Lithium Ions. A -- The instant of the appearance of a crack in specimen 4; B -- Instant of discovery of the p-n defect in specimen 9; C -- Instant of photographing the defect in specimen 9 (see Figure 1).

The variation in the value of the current during the drift of lithium ions through specimen 9 -- where a defect of the p-n junction was discovered (see Figure 1) -- is shown in Figure 5. The current through specimen 4 increased by one order of magnitude when a crack appeared (instant A, in Figure 5), but the current through specimen 9 did not change significantly [at the instant B in Figure 5, a defect was discovered; at the instant C, the defect intensified and a photograph was taken (see Figure 1)]. The current-voltage characteristics of specimen 4, recorded before the appearance of the crack and after its removal, are shown in Figure 6. It is obvious that structural imperfections of the silicon single crystal in the form of a crack have an effect on its electric properties. In all detectors with defects of the p-n junction, no such changes were observed.

We performed experiments allowing us to compare the electric properties of the p-i-n detectors, in which defects of the p-n junction were discovered during the drift of lithium ions, with the electric properties of the detectors, in which no defects were discovered. All the specimens were cut from the same bar, and simultaneously obtained under the same conditions of diffusion and drift of lithium ions. The surface treatment of all the specimens was

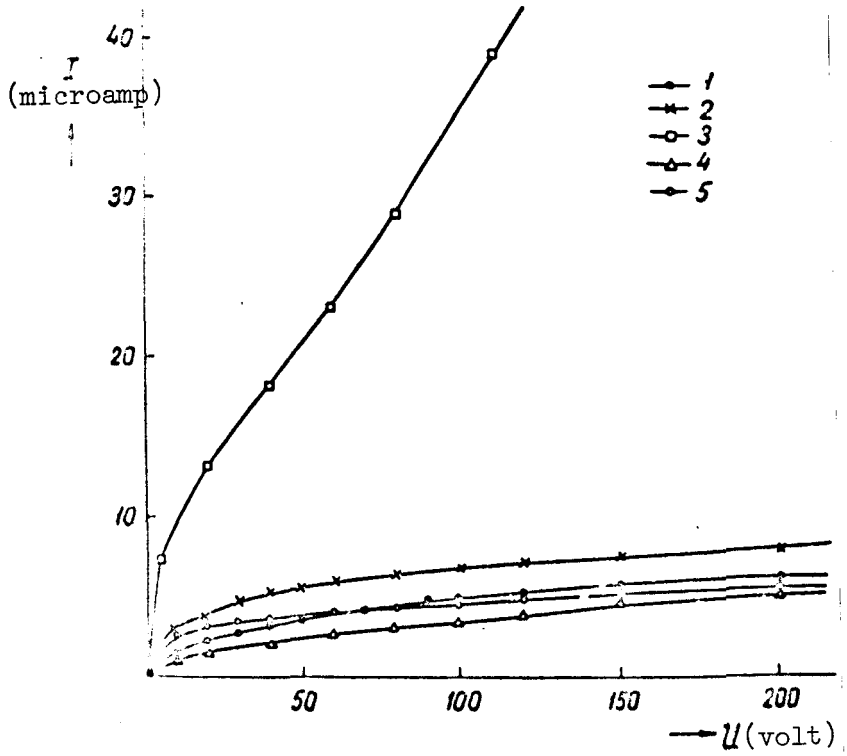

Figure 6

Current-Voltage Characteristics of the p-i-n Silicate Detector in Which a Crack was Discovered. Curve 1 was recorded after 2 hours of drift; Curve 2 -- after 4 hours of drift; Curve 3 -- after 5 hours of drift (crack discovered); Curve 4 -- after removal of the crack; Curve 5 -- after 13 hours of drift.

also conducted in the same way.

Figure 7 shows the current-voltage characteristics of four silicate p-i-n detectors during the drift of lithium ions ("a" -- before diffusion; "b" -- after 4 hours of drift; "c" -- after 20 hours of drift; and "d" -- after 50 hours of drift). In specimens 1 and 2 (curves with dots and triangles), no defects were observed during the drift of lithium ions. In specimen 14 (curve with crosses), a defect of the p-n junction was discovered after 14 hours of drift; in specimen 5 (curve with circles), a defect of the p-n junction was discovered after 50 hours of drift. It may be readily seen that, from the very beginning of drift of lithium ions in silicon, the value of the reverse current in specimens with defects of the p-n junction is considerably

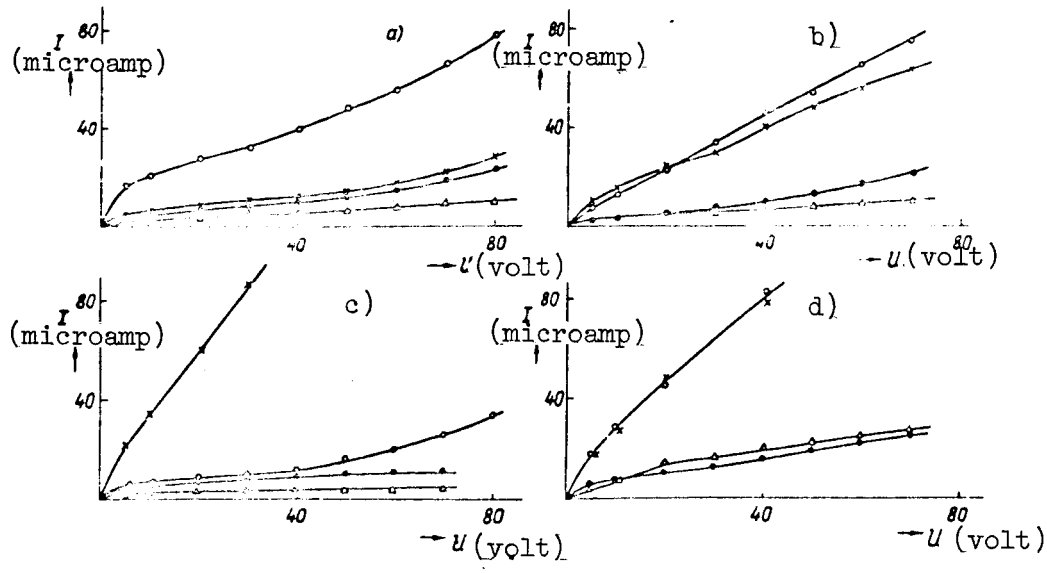

Figure 7

Current-Voltage Characteristics of Four Silicate p-i-n Detectors During the Drift of Lithium Ions: (a) After diffusion; (b) After 4 hours of drift; (c) After 20 hours of drift; (d) After 50 hours of drift; ... -- Specimen 1; ΔΔΔ -- Specimen 2; 000 -- Specimen 5; xx -- Specimen 14. In Specimens 5 and 14, defects of the p-n junction were discovered (see Figures 2 and 3).

greater than in specimens in which there are no defects.

The current through Specimen 9, in which a defect of the p-n junction was observed, is only one order of magnitude larger than the current through Specimen 4, in which no such defect was observed (Figure 8).

Conclusions /6

1. In the present article, we first present the results derived from the investigation of the defects of the p-n junction in silicate p-i-n detectors, generated during the drift of lithium ions. The measurements were conducted simultaneously by the method employing the development of the p-n junction with dry and liquid electrophotographic developers during the application of the reverse bias voltage (on the order of 100 volts), and with the aid of the electrochemical deposition of copper without applying a voltage. The results obtained on the basis of these three methods are identical.

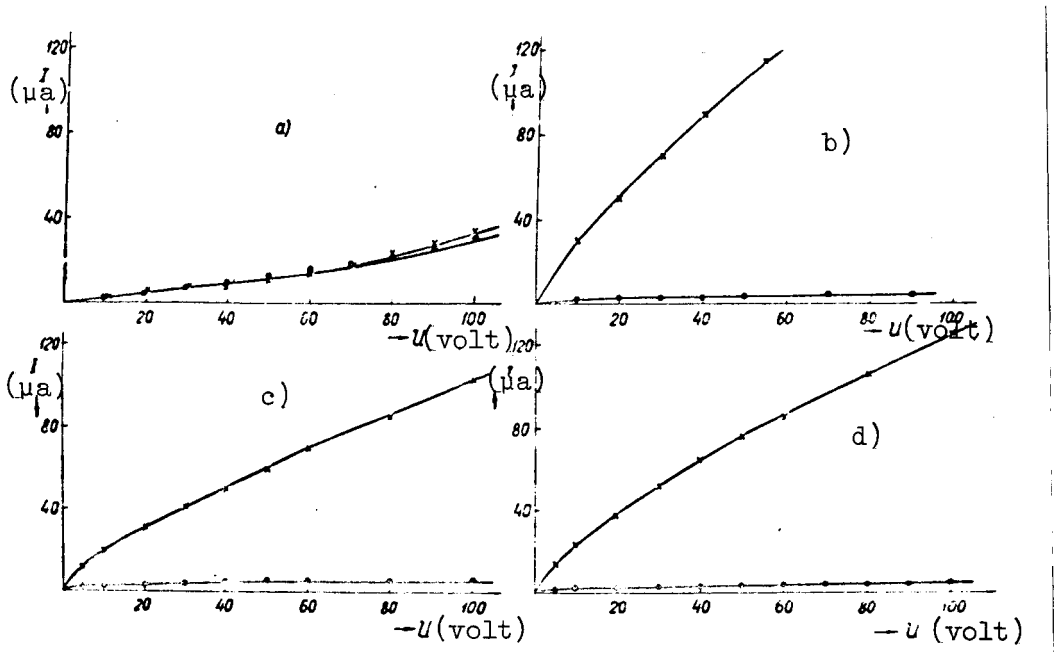

Figure 8

Current-Voltage Characteristic of Two Silicate p-i-n Detectors During the Drift of Lithium Ions: (a) After diffusion; (b) After 2 hours of drift; (c) After 4 hours of drift; (d) After 29 hours of drift.
xxx -- Specimen 9, in which a defect of the p-n junction was discovered (see Figure 1);
... -- Specimen 4 without defects.

2. The defects discovered in the p-n junction of silicate p-i-n detectors lead to large values of the inverse current in the specimens, as compared with the current in specimens without defects. It has been established that no treatment of the surface of a specimen lowers the value of the inverse current to its normal value (2 - 10 microamps at 100 volts). The reverse situation may also be valid. This problem is especially promising with respect to improving the technology of silicate p-i-n detectors.

3. The effect of the defects of the p-n junction, during the drift of lithium ions, upon the process of the formation of a detector region which is sensitive to radiation is fairly complex. It is possible that the discovered defects of the p-n junction are due to the presence of inhomogeneities in the acceptor distribution in a single silicon crystal. In this case, the method of determining defects in the p-n junction during the drift of lithium ions would allow us to measure rather small changes in the density of the acceptor admixtures in silicon, which are of great importance in studying the mechanism by which single crystals are developed by the method of Chokhral'skiy.

4. The method of determining the defects in the p-n junction in the silicate p-i-n detectors during the drift of lithium ions is fully applicable to the investigation of inhomogeneities of the p-n junction and of other semiconductor materials -- in particular, germanium p-i-n detectors.

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